TEMPERATURE AND RATE OF MOISTURE INTAKE IN SEEDS[1]

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(WITH FOUR FIGURES)

Introduction

Some years ago BROWN and WORLEY (1) published an account of some experiments dealing with the influence of temperature on the rate of moisture intake by seeds of barley. They found that the value of Q_{10} for the intake of water is high, approximating that of the van't Hoff law. They interpreted this as indicating that the rate of water absorption through a semipermeable membrane is conditioned by some chemical change which occurs as the temperature rises. In discussing the probable nature of this change they intimate that the water molecule is probably simplified as a result of the temperature rise. In doing so they in a measure accept ARMSTRONG's hydrone theory of the structure of water. Cold water, according to this conception, is composed of complex molecules having at least several H_2O groups combined into a single molecule. These more complex molecules are supposed to break down into simpler groups as the temperature rises; the water becomes less viscous, and is able to penetrate the semipermeable coats of barley seeds more rapidly. The velocity of water intake

[1] Contributions from the Botanical Laboratories of the University of Kentucky, no. 1.

was calculated from the tangents of the curves of intake, using a string and protractor for measuring the tangents. This is a very crude and inaccurate method, especially in unskilled hands, but one easily used. They assert that the velocity of water absorption is almost exactly an exponential function of the temperature.

A short time previous to the appearance of this work the writer (3) had found that the seeds of *Xanthium* have semipermeable coats, and experiments on the influence of temperature on the rate of moisture intake by these seeds were in progress at about the time that BROWN and WORLEY's paper appeared. The results of the work, however, did not receive careful mathematical consideration until about two years later, when it was found that the conclusions reached by BROWN and WORLEY from their work on barley seeds could not be drawn from the data which had been obtained from *Xanthium* seeds. A preliminary report of the work was made before the Botanical Society of America at the Columbus meeting in 1915. The data which had been obtained indicated that the value of Q_{10} was approximately 1.5, somewhat higher than the temperature coefficient of diffusion, but notably lower than that of chemical processes. This situation is very similar to that later reported by DENNY (2) for the effect of temperature on the rate of permeability of certain plant membranes to water.

Shortly following the Columbus meeting a few tests were run on seeds of *Xanthium* having a somewhat different environmental history. Mainly, the seeds were older than those previously used. The intake curves did not check very well with the former data, and it was thought desirable to repeat the experiments with seeds of the same species of *Xanthium* but of different genetic origin and environmental history. In this way it was felt that data might be obtained regarding the variability in the rate of water absorption in these seeds. The data which have been accumulated have been subjected to a critical analysis, principally to insure accuracy in the measurements of tangents. At the same time the possibility of a rate law has been kept in mind; but from a study of absorption in a number of cases I have decided that it would be unsafe or at least premature to propose a rate law on the basis of data now obtained. At the same time, the formulae presented may have

rather wide application, and deserve to be considered by those interested in the problems of absorption. While on the theoretical side certain features of the work have been disappointing, it will be worth while to give a somewhat detailed account of the experiments, as a contribution to our knowledge of the facts concerning the intake of water by dry organized matter.

I wish to acknowledge my indebtedness to Professor S. P. Shull for valuable assistance with the mathematical part of the work. He has given generously of his time during the last five years to a painstaking analysis of the data, which has made possible a degree of accuracy otherwise unobtainable, and without which the general significance of the data could not have been fully appreciated. He has also tested many hypotheses as to the influence of factors upon intake rates. The principal part of the experimental work was done in the Laboratory of Plant Physiology at the University of Kansas, and part of it at the University of Chicago during the summer of 1914. The privileges of the Hull Botanical Laboratory for this work were much appreciated.

Materials and methods

The experiments were carried on with the lower seeds of *Xanthium pennsylvanicum* Wallr., and the naked cotyledons of several varieties of peas, the Canada green field pea, the Tom Thumb garden pea, and the Small Scotch Yellow pea of commerce. The cockleburs were chosen for their semipermeable coats, and the peas because the elimination of coat effects is easy. At first seeds of *Xanthium* were collected in the field; but these were soon replaced by pure line seeds grown on the breeding grounds of the University of Kansas in 1913. It was felt that such seeds might be more valuable than those of mixed genetic origin, more uniform in behavior, and the absorption data therefore more susceptible to mathematical consideration. After it had become evident that age, environmental history, genetic origin, and other factors might influence the intake phenomena, seeds were obtained from plants growing near the writer's home in Lawrence, Kansas. Slight differences in the shape and appearance of the seeds of different plants indicated possible lack of genetic purity, although the

plants by all their external characteristics were unmistakably true *X. pennsylvanicum*. These were used in the later work to give an idea of the variability to be encountered in the moisture intake by a given kind of substance.

The absorption took place in test-tubes of distilled water which were kept at the desired temperature by standing them in a water bath. Care was taken, particularly in the later work, to have the seeds at the same temperature as the water when they were first brought together. Three temperature curves are discussed in the present paper, 5, 20, and 35° C. Tests were run at 5° intervals from 5° to 50° C., but these three stand near to the temperatures used by BROWN and WORLEY, and afford a satisfactory basis for comparison. The others have been omitted. In all cases the fluctuation rarely exceeded 0.25° on either side of the chosen temperature during the significant period of intake.

At close intervals the seeds were removed from the water, dried uniformly and quickly on filter paper, and weighed with analytical accuracy. The time periods of immersion were made as sharp and accurate as possible, and the time during which the seeds were out of the water was reduced to the lowest possible limit. The drying required 10–20 seconds usually, and the weighing was done as rapidly as accuracy permitted. During this period the seeds had some opportunity to change from the temperature of absorption in the 5° and 35° tests, but histeresis of the seed colloids would tend to prevent serious alterations in colloidal aggregation during the brief interval involved. The errors due to such changes would be slight. The intervals between weighings were made short throughout the work. The first weighing was always made at the end of 1 minute to catch the very rapid initial intake. Succeeding intervals were usually 10 or 15 minutes, or longer when continuous attention could not be given to the work. The time intervals used will always be indicated in the tables with the absorption data. In all cases the time needed for drying and weighing was subtracted. This weighing at intervals was continuous in the case of *Xanthium* seeds until the intake was well above 35 per cent out of a possible 50–55 per cent. By the time 40 per cent of water had been taken in, the velocity of intake always

showed marked and increasing depression, due to approaching saturation. The split peas take up a considerably larger percentage of water than *Xanthium* seeds, and the intervals were continued until intake significant for the problem in hand had ceased.
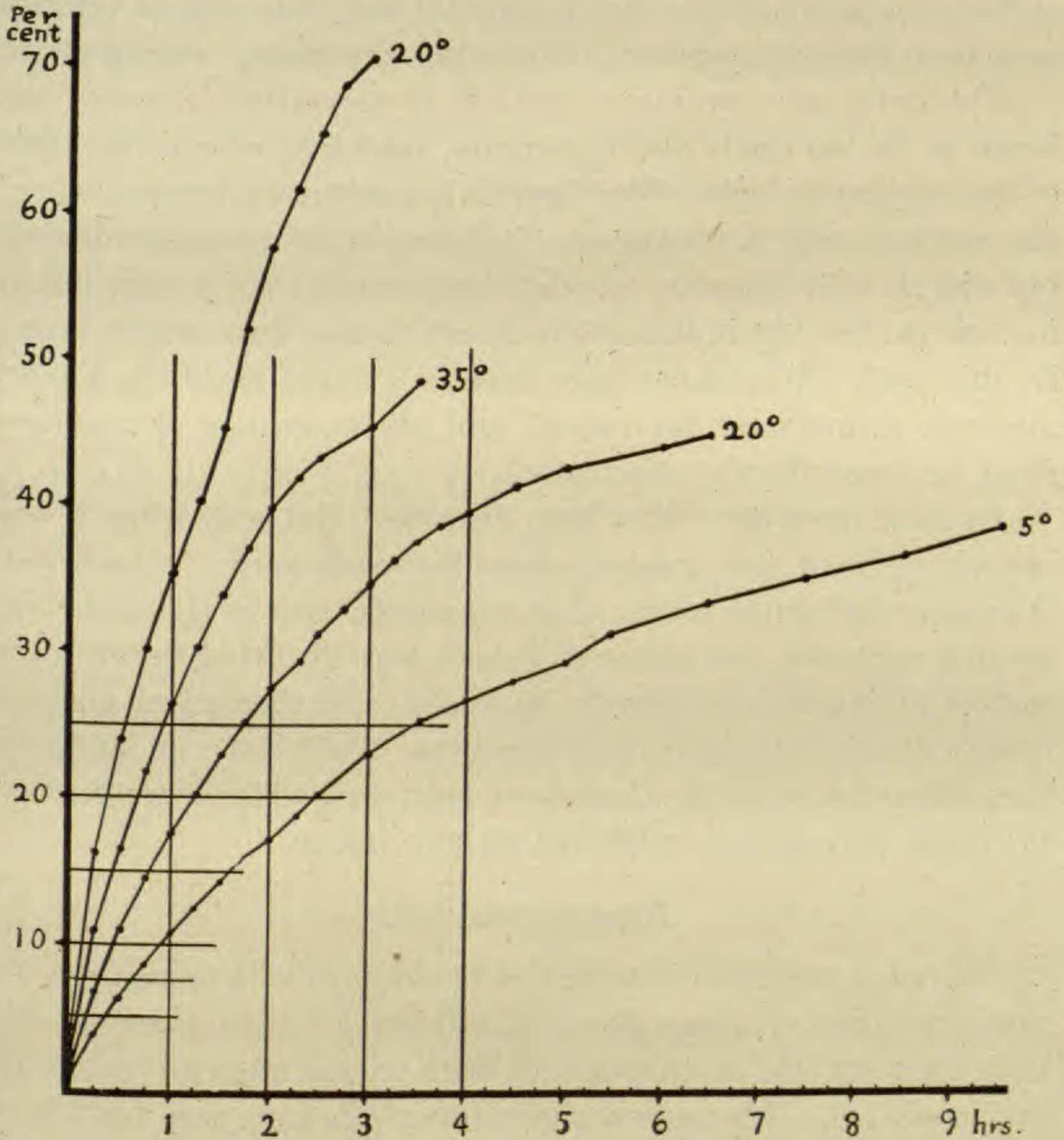
FIG. 1.—Curves of moisture intake: lowest curves, 5, 20, and 35°, by *Xanthium* seeds; upper curve, split peas, 20°; horizontal lines show points of equal intake where tangents were measured.

The value of close time intervals, despite certain obvious disadvantages, will be indicated later in discussing the work of BROWN and WORLEY.

The velocity of intake at any given moment has been calculated from the tangents to the curves. By reference to fig. 1 it will be

seen that horizontal lines cut the three temperature curves for *Xanthium* seeds at 5, 7.5, 10, 15, 20, and 25 per cent of intake. The tangents were determined at the points where these horizontal lines of equal intake cut the curves. From the velocity of intake at the three points cut by each horizontal line, the ratios of velocity have been derived, and from these ratios the mean value of Q_{10}.

The string and protractor method of measuring tangents was found to be too crude and inaccurate, especially where the angle of the tangent is high. The English investigators, however, used the method with fair success. Their measured tangents deviate but slightly from tangents calculated accurately for the same points in their curves, but in less skilful hands serious error might occur. In this work all tangents have been calculated from the known algebraic formulae of the curves, and all inaccuracy of measurement has been thereby eliminated.

In some cases data have been discarded, but only when it was entirely justified, and necessary from the mathematical standpoint. Whenever during the course of an experiment any of the seed coats became ruptured, the curve of intake was distorted because the surface of intake was greatly increased. Mathematical analysis of such data is impossible or meaningless. Such series of data have been discarded, and only those have been used which went through the many dryings and weighings without injury.

Experimental data

The data presented in table I were obtained with seeds from the first generation of a pure line of *Xanthium pennsylvanicum* Wallr., from the same line as was used for work on soil moisture published previously (4). The general characters of the type used have been described as type II in a discussion (5) of physiological isolation in the genus. The series of data chosen for mathematical consideration were drawn from a large mass of data some time before the analysis was made, solely on the basis of maintenance of satisfactory conditions during the period of observation. Ten lower seeds of *X. pennsylvanicum* were used in each case.

The series at any given temperature were fairly uniform with these seeds at the time the work was done. The variability to

be encountered is illustrated very well by the duplicate tests presented for 5° C.

The earlier work on split peas was not very satisfactory. They are more difficult to dry uniformly, and small pieces are more easily lost from the edges of the cotyledons during the drying, especially at higher temperatures. In table II data are given for two tempera-

TABLE I

WATER INTAKE OF *Xanthium* SEEDS IN PERCENTAGE OF AIR-DRY WEIGHT

TIME	5°		20°	35°
	I	II	I	I
1 minute........	1.124	1.36	1.73	2.45
15 minutes......	3.814	4.23	6.806	10.89
30 minutes......	6.226	6.18	11.00	16.41
45 minutes......	8.544	8.32	14.55	21.81
60 minutes......	10.747	9.92	17.38	26.38
75 minutes......	12.521	11.90	20.20	30.21
90 minutes......	14.202	13.05	22.81	33.89
105 minutes......	15.710	14.65	25.12	37.11
120 minutes......	17.101	15.81	27.44	39.80
135 minutes......	18.724	17.65	29.32	41.87
150 minutes......	20.182	19.81	31.06	43.25
165 minutes......	....	20.90	32.80	....
180 minutes......	23.002	22.27	34.54	45.24
195 minutes......	....	23.40	36.13	....
210 minutes......	25.159	24.54	37.43	48.46
225 minutes......	....	26.54	38.52	....
240 minutes......	26.701	....	39.39	....
255 minutes......	....	27.96	....	....
270 minutes......	27.965	....	40.98	....
290 minutes......	....	29.56	....	....
300 minutes......	29.182	....	42.57	....
330 minutes......	31.304	31.00	....	....
360 minutes......	....	....	43.95	....
390 minutes......	33.159	....	44.75	....
450 minutes......	35.072	....	....	....
510 minutes......	36.486	....	....	....
570 minutes......	38.400	....	....	....
18.5 hours......	45.020	....	....	....
26 hours......	....	....	47.28	....

tures only, 20 cotyledons being used for each measurement. Curves of intake have been plotted for the cocklebur seeds at all three temperatures, and for the split peas at 20° C. in fig. 1. The split peas are included here merely to show how various substances differ in rate of intake at the same temperature. The rate of

intake, of course, varies with physical structure, chemical composition, state of aggregation of colloids, etc.

TABLE II

WATER INTAKE OF COMMERCIAL SPLIT PEAS (VARIETY UNKNOWN) IN PERCENTAGE OF AIR-DRY WEIGHT

Time	20°	35°
1 minute..........	4.25	5.30
15 minutes..........	16.20	20.83
30 minutes..........	23.84	33.04
45 minutes..........	30.14	41.94
60 minutes..........	35.32	50.30
75 minutes..........	40.30	57.60
90 minutes..........	45.22	63.77
105 minutes..........	52.06	67.81
120 minutes..........	57.50	71.00
135 minutes..........	61.42	....
150 minutes..........	65.34	....
165 minutes..........	68.66	74.32
180 minutes..........	70.32	....
195 minutes..........	72.18	....
210 minutes..........	72.97	....
285 minutes..........	....	76.11
330 minutes..........	74.96	....
22 hours..........	....	77.50
22.5 hours..........	74.96	....

TABLE III

WATER INTAKE BY *Xanthium* SEEDS IN PERCENTAGE OF AIR-DRY WEIGHT, 5° C.

Time (minutes)	I	II	III	IV	V	Percentage of averages
1..........	1.30	1.90	1.33	2.19	1.57	1.64
5..........	3.29	3.25	3.70	3.87	3.33	3.44
10..........	4.74	4.47	5.25	5.92	4.90	4.97
15..........	6.20	5.55	6.88	6.87	6.15	6.22
30..........	8.49	8.13	9.02	9.72	8.92	8.72
45..........	10.79	10.43	11.09	11.76	10.87	10.82
60..........	12.85	11.79	13.02	13.00	12.81	12.50
90..........	15.68	14.50	15.53	16.73	15.89	15.43
120..........	18.36	16.87	18.05	18.85	18.09	17.77
150..........	21.04	18.97	20.56	20.67	20.29	19.99
180..........	22.88	20.73	22.71	22.42	22.30	21.86
240..........	26.55	24.39	25.89	26.08	26.26	25.42
300..........	30.22	27.51	28.99	29.07	29.71	28.67
360..........	33.59	30.28	32.03	31.92	32.91	31.67
420..........	37.18	32.25	34.91	35.14	35.30	34.55
540..........	40.93	36.86	39.20	39.96	40.70*	38.56

* During the last two hour period in no. V the mean temperature was about 6.2° C.

After the earlier work had been analyzed, some tests were made on old seeds remaining on hand, in an effort to check up the initial

absorption rates.   As the seeds seemed to show a somewhat different behavior, tending to decreased intake rates at the start, it was

TABLE IV
WATER INTAKE BY *Xanthium* SEEDS IN PERCENTAGE OF AIR-DRY WEIGHT, 20°C.

Time (minutes)	I	II	III	IV	V	VI	Percentage of averages
1	1.77	1.95	3.32	2.35	2.72	2.08	2.38
5	4.60	5.28	6.15	5.56	5.44	4.94	5.34
10	6.76	8.21	8.59	8.26	8.21	7.41	7.94
15	8.44	11.44	10.45	11.07	10.28	10.27	10.32
30	11.79	13.88	14.69	14.98	16.51	16.51	14.64
45	15.10	17.15	17.97	18.83	22.15	20.68	18.54
60	17.64	20.33	20.51	21.53	23.84	23.67	21.13
75	19.94	22.29	22.95	24.29	26.90	26.27	23.64
90	21.81	24.63	25.78	26.79	29.18	28.87	26.04
105	23.78	26.88	27.56	29.19	31.21	31.21	28.17
120	25.89	28.84	29.88	31.10	32.59	33.42	30.14
135	28.00	31.33	31.69	32.95	34.47	35.63	32.16
150	29.53	32.50	33.20	34.30	36.10	37.84	33.72
165	31.35	34.31	34.56	35.75	37.09	39.27	35.20
180	32.89	35.48	35.84	37.20	38.77	40.96	36.66
195	34.32	36.46	36.91	38.11	39.61	42.46	37.77
210	....	37.54	37.79	39.01	40.50	43.69	38.79
225	....	....	38.86	40.01	41.44	44.73	....
240	37.68	....	39.45	40.86	42.33	45.77	40.64
300	40.27	41.84	41.55	44.56	....	....	....

TABLE V
WATER INTAKE BY *Xanthium* SEEDS IN PERCENTAGE OF AIR-DRY WEIGHT, 35° C.

Time (minutes)	I	II	III	IV	V	VI	VII	VIII	Percentage of averages
1	2.21	2.46	3.73	2.84	2.46	2.75	3.76	2.44	2.83
5	6.35	7.37	9.28	7.61	5.88	6.19	9.92	7.04	7.46
10	10.22	11.37	15.40	11.34	9.78	10.25	14.98	11.10	11.82
15	14.23	14.59	20.24	14.25	12.31	12.79	18.47	13.80	15.11
20	16.85	17.36	23.13	17.15	14.09	15.34	21.41	16.51	17.84
30	21.28	22.58	27.77	21.85	19.49	19.95	25.44	21.25	22.45
40	25.14	26.42	31.94	25.45	23.67	23.52	28.86	25.44	26.32
50	28.80	30.18	34.90	29.25	27.09	26.82	31.81	26.69	29.70
60	32.39	33.79	37.66	32.85	30.16	30.12	34.68	31.94	32.95
70	35.15	36.64	40.01	35.20	33.11	33.29	37.21	35.05	35.71
80	37.29	39.48	42.23	37.76	35.50	36.31	39.33	37.21	38.13
90	39.23	41.78	44.05	39.70	37.62	38.79	41.18	39.24	40.19
100	39.50	43.78	45.53	41.22	39.67	40.92	42.75	41.00	41.78

felt that studies should be made of absorption in ordinary field material, with the purpose of disclosing the variability likely to occur at a given age of seeds.   These experiments were conducted

through a period of several weeks on seeds ripened for about three months. To reduce the time element in drying and weighing, only two seeds were used in each test. At the same time care was taken to have the temperature of seeds and water equal at the beginning of the measurements in each test. Table III shows the results of

TABLE VI

WATER INTAKE IN SPLIT PEAS IN PERCENTAGE OF AIR-DRY WEIGHT

Time (minutes)	Tom Thumb Yellow			Green Canada field pea			Small Scotch Yellow		
	5°	20°	35°	5°	20°	35°	5°	20°	35°
1....	3.00	3.76	4.38	3.17	4.09	5.54	1.77	5.38	5.77
5....	7.28	8.60	10.19	7.98	9.20	14.01	7.26	13.26	16.34
10....	10.48	12.63	14.90	11.73	13.49	20.30	11.50	19.98	26.54
15....	13.05	15.50	18.69	14.61	16.68	25.62	15.58	25.09	33.65
20....	....	....	22.10	....	....	30.94	....	....	41.54
30....	16.79	21.15	27.78	19.33	22.98	41.59	22.48	33.69	54.23
40....	....	....	32.24	....	....	52.33	....	....	63.75
45....	20.02	26.16	....	23.08	28.78	....	26.64	....	....
48....	....	....	....	....	....	....	....	43.01	....
50....	....	....	36.78	....	....	68.24	....	....	69.04
60....	22.83	30.11	42.34	26.35	34.96	80.40	29.82	50.89	73.56
70....	....	....	50.34	....	....	89.36	....	....	74.04
75....	25.67	33.33	....	29.23	42.52	....	36.37	58.24	....
80....	....	....	59.05	....	....	92.73	....	....	....
90....	28.09	37.28	64.27	32.31	50.41	94.68	40.00	69.59	....
100....	....	....	68.69	....	....	96.25	....	....	....
105....	30.58	45.34	....	35.91	64.76	....	43.37	68.10	....
120....	33.00	51.61	....	38.17	73.96	....	45.66	70.34	....
135....	....	57.21	....	....	79.48	....	48.85	72.58	....
150....	36.81	62.01	....	43.89	82.99	....	51.86	....	....
165....	....	67.16	....	....	....	....	54.07	....	....
180....	40.79	70.74	....	48.94	....	....	....	....	....
210....	44.92	....	....	55.10	....	....	....	....	....
225....	....	....	....	....	....	....	61.59	....	....
240....	49.40	....	....	66.87	....	....	....	....	....
270....	54.42	....	....	68.22	....	....	....	....	....
300....	60.19	....	....	72.60	....	....	....	....	....
330....	66.11	....	....	....	....	....	....	....	....
345....	....	....	....	....	....	....	69.91	....	....
360....	71.87	....	....	....	....	....	....	....	....
390....	73.67	....	....	....	....	....	....	....	....

five experiments at 5° C. In the last column is shown the percentage of the averages of intake. This percentage of the averages must not be confused with the average of the percentages, which would give a slightly different set of figures. In analyzing these variable groups we have used the percentage of the averages in attempting to construct a mathematical curve that would follow

the data. Similar groups of data for 20° and 35° C. are shown in tables IV and V.

The absorption data for the split peas were found on examination to be very difficult to analyze, owing to changes in rate of absorption, due almost certainly to internal physical changes in the seed. No attempt was made to carry out the work in so detailed a manner as in the case of *Xanthium* seeds. Enough has been done, however, to make it worth while to put the data on record. The results with three named varieties of peas at the three chosen temperatures are given in table VI.

Mathematical discussion

For purposes of mathematical discussion it is not considered essential to plot any curves of the data in addition to those given in fig. 1. Only such curves are used as are necessary to an understanding of the discussion. Anyone desiring the curves can easily plot them from the data.

In view of the fact that BROWN and WORLEY considered the curves of water absorption in *Hordeum* seeds as paraboloid running out toward a common asymptote, attention was turned first to the type of curve which would most nearly fit the data shown in the preceding tables. Even a casual examination of the data of tables I and II shows that the curves are not simple ones. Since the situation is somewhat simpler in the case of *Xanthium* seeds than in the split peas, the data from the former will be considered first.

Xanthium seeds

During the first moments of absorption (40–60 seconds) the entrance of water is exceedingly rapid; but in a short time the rate breaks sharply to a lower rate, which then decreases slowly but rather steadily during the main part of absorption, until approaching saturation begins to affect the rapidity of intake. In *Xanthium* seeds saturation occurs at about 50 per cent, and the final break in the curve caused by approaching saturation manifests itself at about 35–40 per cent, as is shown in the figures. The whole curve is thus apparently a composite curve made

up of at least three component curves. The general relations of these to one another in the composite curve are shown graphically in fig. 2, which has been somewhat exaggerated, especially in respect of the first curve, for the sake of clearness. The effect of the initial rapid intake is to throw the main part of the curve upward from the base line. Careful examination showed that it was not possible to find a parabolic curve that would follow the data at any temperature. The problem then was to find an empirical formula or equation or such a combination of equations as would very closely approximate the given data of observation. This was necessary
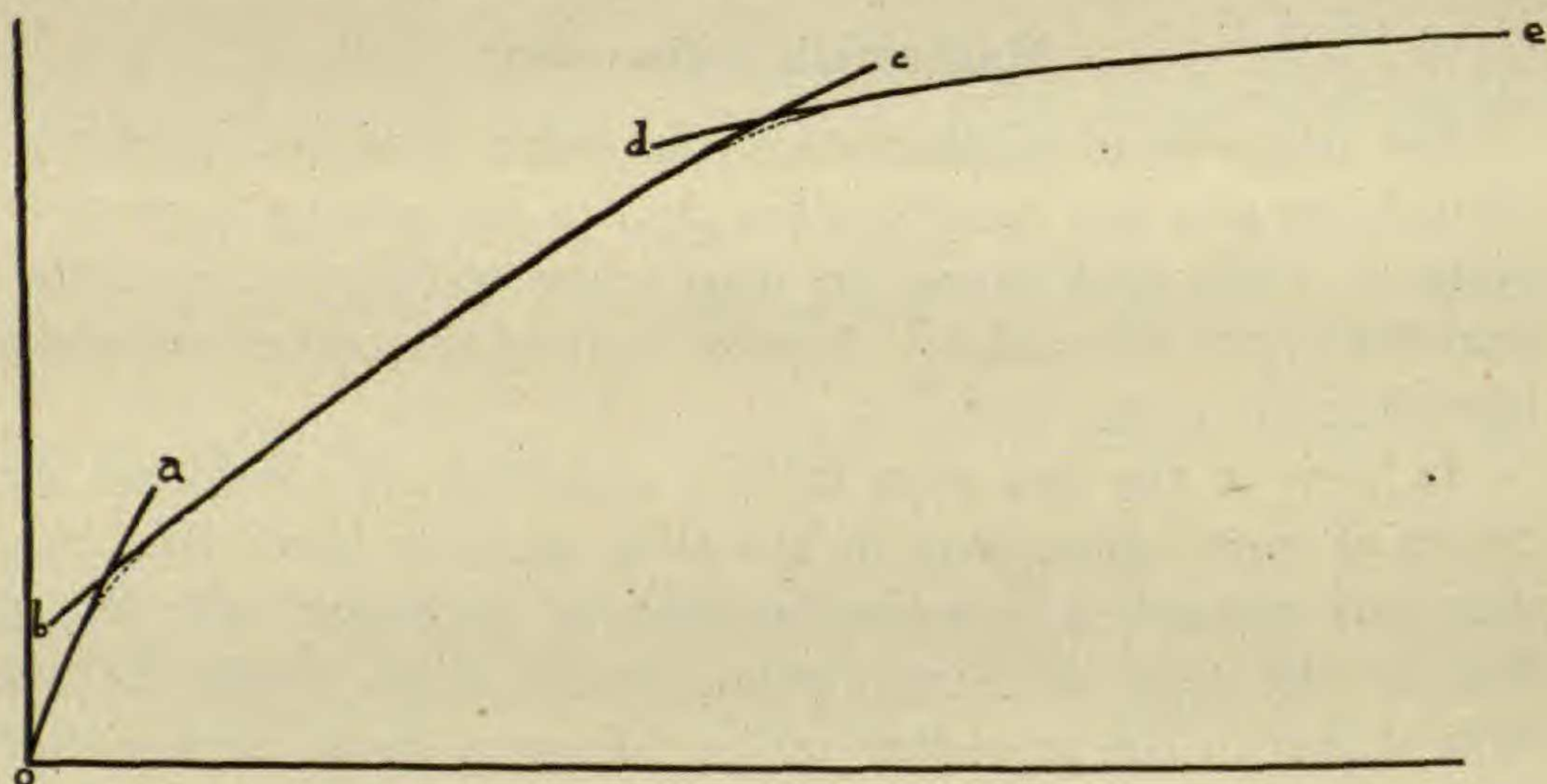
Fig. 2.—Curves showing composite nature of moisture intake curves in *Xanthium*: first curve exaggerated; *oa*, initial intake; *bc*, main curve; *de*, approaching saturation.

in order that precise and accurate methods of measuring tangents could be substituted for the uncertainties of the graphic method used by Brown and Worley. The only proof we have that any equation or group of equations is adapted to such use lies in a comparison of the experimental data with corresponding values computed from the equation under consideration. As it is impossible to avoid slight irregularities in obtaining data, the equation must be so determined as to distribute the irregularities rather evenly on either side of the curve, as one would expect from the laws of chance variation.

Early in the investigation an equation was discovered which could be made to approximate very closely the series of data

obtained by measuring the total increase in weight due to absorption for different periods of immersion. This equation takes the form $y = a \log_{10}(bx+1)+c$, in which $y =$ the total percentage of intake, and $x =$ the length of time of immersion, a, b, and c being constants. In the later work it was found that a still closer approximation could be obtained by the employment of two equations of this form tangent to each other, the first equation representing the

TABLE VII

ALGEBRAIC CURVE FOR ABSORPTION DATA AT $5°$ C.; ABSORPTION
IN PERCENTAGE OF AIR-DRY WEIGHT (*Xanthium*)

Time	Data low	Computed	Data high
1 minute........	....	1.055	1.124
15 minutes......	....	3.739	3.814
30 minutes......	6.226	6.279	....
45 minutes......	8.544	8.545	....
60 minutes......	....	10.591	10.747
75 minutes......	....	12.456	12.521
90 minutes......	....	14.169	14.202
105 minutes......	15.710	15.753	....
120 minutes......	17.101	17.226	....
135 minutes......	....	18.603	18.724
150 minutes......	19.810*	19.896	....
165 minutes......	20.900*	21.113	....
180 minutes......	....	22.265	22.270*
195 minutes......	....	23.356	23.400*
210 minutes......	....	24.394	24.540*
240 minutes......	....	26.327	26.701
270 minutes......	27.965	28.098	....
300 minutes......	29.182	29.732	....
330 minutes......	....	31.247	31.304
390 minutes......	33.159	33.987	....
450 minutes......	35.072	36.410	....
510 minutes......	36.486	38.583	....
570 minutes......	38.400	40.524	....
18.5 hours......	45.020	52.975	....

*Data from series II.

earlier data, the second representing the later data beyond the point of tangency. In one case it was found advantageous to introduce a third equation of this kind. The closeness with which this equation can be made to approximate the experimental data is truly surprising. It has been applied to the data furnished by BROWN and WORLEY for barley seeds, and approximates their data more closely than the calculated values they obtained from their formula. It must not be supposed, however, that the formula

can be successfully applied to all cases of absorption, or that it has any special significance beyond its applicability to measuring tangents accurately in all curves to which it fits.

In dealing with the data of table I it was found desirable to partially combine the two series at 5° C. because of irregularities in each set. As the seeds used in these early tests were not reduced to water temperature before immersion, some tests were run for

TABLE VIII

ALGEBRAIC CURVES FOR ABSORPTION DATA; INTAKE IN PERCENTAGE OF AIR-DRY WEIGHT (*Xanthium*)

TIME	20° C			TIME	35° C		
	Data low	Computed	Data high		Data low	Computed	Data high
1 minute . .	1.73	1.821	. . . .	1 minute. .	2.45	2.840	. . . .
15 minutes..	. . . .	6.481	6.806	15 minutes..	. . . .	10.136	10.89
30 minutes..	. . . .	10.599	11.00	30 minutes..	16.41	16.471	. . . .
45 minutes..	. . . .	14.213	14.55	45 minutes..	. . . .	21.720	21.81
60 minutes..	17.38	17.396	. . . .	60 minutes..	. . . .	26.317	26.38
75 minutes..	20.20	20.239	. . . .	75 minutes..	30.21	30.305	. . . .
90 minutes..	. . . .	22.809	22.81	90 minutes..	. . . .	33.855	33.89
105 minutes..	25.12	25.153	. . . .	105 minutes..	. . . .	37.054	37.11
120 minutes..	. . . .	27.308	27.44	120 minutes..	39.80	39.964	. . . .
135 minutes..	. . . .	29.301	29.32	135 minutes..	41.87	42.635	. . . .
150 minutes..	31.06	31.157	. . . .	150 minutes..	43.25	45.102	. . . .
165 minutes..	32.80	32.891	. . . .	180 minutes..	45.24	49.534	. . . .
180 minutes..	. . . .	34.520	34.54	7 hours....	48.46	72.348	. . . .
195 minutes..	. . . .	36.056	36.13				
210 minutes..	37.43	37.507	. . . .				
225 minutes..	38.52	38.884	. . . .				
240 minutes..	39.39	40.194	. . . .				
270 minutes..	40.98	42.634	. . . .				
300 minutes..	42.57	44.871	. . . .				
330 minutes..	43.95	46.934	. . . .				
360 minutes..	44.75	48.849	. . . .				
26 hours....	47.28	84.280	. . . .				

corrections of initial intake with seeds at water temperature. The result was a slight lowering of the initial intake at 5° C., and an increase at 35° C. These corrections were taken into consideration in deriving the values of the constants for computing the theoretical intake from the formula.

In the 5° C. curve the values for the constants a, b, and c in the equation given are as follows: $y = 48.5 \log_{10} (0.098x + 1) + 0.85$. The closeness of the intake computed from this equation to the actual data is illustrated in tables VII and VIII.

The computed intake agrees very well with the experimental data until the absorption reaches 33 per cent, and from that on the data fall more and more below the computed values. This falling off of the actual intake marks the beginning of the effects of approaching saturation. It is evident that tangents to the curve may safely be computed up to about 35 per cent of intake, but beyond that point the tangents could not be used for comparisons of the rate of intake in different curves.

For the absorption at 20° C. the substituted values for the constants make the equation read $y = 61.5 \log_{10}(0.0136x + 1) + 1.46$, and the corresponding equation for 35° C. is $y = 74.5 \log_{10}(0.0184x + 1) + 2.25$. The closeness of the computed intake to the data of observation in each case is shown in table VIII.

In the 20° curve the effects of approaching saturation first manifest themselves at about 37.5 per cent, and in the 35° curve at about 40 per cent of intake. In each curve the computed values are strikingly close to the actual data. The uniformity of absorption and the agreement of the calculated intake to that observed has been a surprising feature of the work; and since the final break due to approaching saturation is always at or beyond 35 per cent, I have felt confident of accuracy in measuring tangents of the curves to that point.

In the later work the data could not be so satisfactorily represented by means of a single equation. By the use of two or three successive equations, however, each joined to its successor in a point of equal tangency, a very close agreement between calculated intake and experimental data was obtained. For the purpose of calculating tangents, and rates of intake, this composite curve is just as satisfactory as if it were developed from a single equation.

The 5° curve will be considered first. The three empirical equations used are as follows:

(1) $y = 14.3 \log_{10}(0.078x + 1) + 1.398$

(2) $y = 35.07 \log_{10}(0.0121x + 1) + 4.195$

(3) $y = 87.95 \log_{10}(0.0023x + 1) + 8.625$

The first two curves have equal tangents for $x = 35.35$, and the last two for $x = 150.89$ (minutes). The breaks in the curve

are very small. Thus, at the first break, in curve 1, $y = 9.605814$; while in curve 2, $y = 9.6056$ at the common point of tangency with curve 1. At this common point the two curves are only 0.000214 (per cent) apart. Similarly at the second break, for curve 2, $y = 20.01634$, and for curve 3, $y = 20.016284$, a break of only 0.000056 per cent. This combination curve runs remarkably close to the data of observation and gives perhaps the best series presented. The calculated and observed intake is shown in table IX. Data in last column, table III.

TABLE IX

ALGEBRAIC CURVES FOR ABSORPTION DATA; INTAKE IN PER-
CENTAGE OF AIR-DRY WEIGHT (*Xanthium*), 5° C.

Time (minutes)	Data low	Computed	Data high
1	1.64	1.86	
5		3.44	
10	4.97	4.98	
15		6.21	6.22
30	8.77	8.89	
45		10.82	
60	12.50	12.51	
90		15.42	15.43
120	17.77	17.86	
150		19.96	19.99
180		21.86	
240		25.41	25.42
300		28.67	
360		31.67	
420		34.46	34.55
540	38.56	39.46	

The data obtained with *Xanthium* seeds at 20 and 35° C. were given similar treatment. Two equations were used for the 20° data as follows:

(1) $y = 23.77 \log_{10}(0.088x + 1) + 1.524$

(2) $y = 57.13 \log_{10}(0.0132x + 1) + 6.616$

These two curves have tangents equal for $x = 34.52$, at which point curve 1 has $y = 15.931972$, and curve 2, $y = 15.931732$, only 0.00024 per cent apart.

In the 35° data, also, two successive equations were used:

(1) $y = 34.92 \log_{10}(0.0983x + 1) + 1.40$

(2) $y = 73.05 \log_{10}(0.0286x + 1) + 6.53$

The point of equal tangency in these curves comes at $x = 22.91$, and at this point in curve 1, $y = 19.28409$, while in curve 2, $y = 19.28407$. The break therefore is only 0.00002 per cent. The agreement between computed and observed intake here is not quite so close as in the 5° curve, but is still very good (see table X, the data for which come from the final columns of tables IV and V).

It is apparent in these later results, just as in the earlier ones, that approaching saturation does not begin to interfere with absorption rates until 35–40 per cent of intake has occurred. It should be quite clear, also, that the equations employed run so

TABLE X

ALGEBRAIC CURVES FOR ABSORPTION DATA; INTAKE IN PERCENTAGE OF AIR-DRY WEIGHT (*Xanthium*)

TIME (MINUTES)	20°			TIME (MINUTES)	35°		
	Data low	Computed	Data high		Data low	Computed	Data high
1	2.38	2.39	....	1	....	2.82	2.83
5	....	5.29	5.34	5	....	7.46	....
10	7.92	8.05	....	10	....	11.78	11.82
15	....	10.21	10.32	15	15.11	15.14	....
30	14.64	14.86	....	20	17.84	17.89	....
45	....	18.18	18.54	30	....	22.38	22.45
60	....	21.09	21.13	40	....	26.29	26.32
75	23.64	23.69	....	50	29.70	29.76	....
90	....	26.04	....	60	....	32.90	32.95
105	28.17	28.19	....	70	35.71	35.75	....
120	30.14	30.17	....	80	38.13	38.37	....
135	....	32.00	32.18	90	40.19	40.79	....
150	....	33.71	33.72	100	41.78	43.03	....
165	35.20	35.30	....				
180	36.66	36.80	....				

close to the observed data that the velocity of intake can be measured at any given moment with great accuracy. Instead of plotting curves and attempting to measure the tangents graphically, they have been calculated from the known formula.

The velocity of intake has been computed from the tangents for six points on each temperature curve of intake. These points coincide with those chosen by BROWN and WORLEY, as follows: 5, 7.5, 10, 15, 20, and 25 per cent of intake. The percentage hourly rate of intake for these points, on each curve shown in tables VII and VIII, together with the logarithms of the hourly rates of intake, are shown in table XI.

TABLE XI

WATER INTAKE IN *Xanthium* SEEDS

INTAKE PERCENTAGE	5°		20°		35°	
	Velocity in percentage per hour	Logarithm	Velocity in percentage per hour	Logarithm	Velocity in percentage per hour	Logarithm
$y=5$	10.1705	1.007342	19.0894	1.280792	32.8097	1.516002
$y=7.5$	9.0322	0.955794	17.3838	1.240145	30.3700	1.482445
$y=10$	8.0214	0.904250	15.8304	1.199492	28.1116	1.448886
$y=15$	6.3264	0.801157	13.1278	1.118191	24.0865	1.381774
$y=20$	4.9896	0.698066	10.8866	1.036893	20.6376	1.314659
$y=25$	3.9351	0.594956	9.0280	0.955592	17.6826	1.247546

In the later work the velocity calculated from the tangents is expressed in percentage per minute, instead of percentage per hour. The velocities for the same six points, on the curves shown in tables IX and X, are given in table XII.

TABLE XII

WATER INTAKE IN *Xanthium* SEEDS

INTAKE PERCENTAGE	5°		20°		35°	
	Velocity in percentage per minute	Log$_{10}$ Velocity	Velocity in percentage per minute	Log$_{10}$ Velocity	Velocity in percentage per minute	Log$_{10}$ Velocity
$y=5$	0.27122	$\bar{1}.433322$	0.64872	$\bar{1}.812057$	1.17576	0.070318
$y=7.5$	0.18134	$\bar{1}.258494$	0.50920	$\bar{1}.706888$	0.99707	$\bar{1}.998726$
$y=10$	0.12589	$\bar{1}.099992$	0.39968	$\bar{1}.601702$	0.84554	$\bar{1}.927134$
$y=15$	0.09066	$\bar{2}.957416$	0.24624	$\bar{1}.391358$	0.60806	$\bar{1}.783947$
$y=20$	0.06537	$\bar{2}.815378$	0.19096	$\bar{1}.280943$	0.44820	$\bar{1}.651472$
$y=25$	0.05722	$\bar{2}.757548$	0.15611	$\bar{1}.193431$	0.38284	$\bar{1}.583018$

TEMPERATURE COEFFICIENT.—Having now obtained the rate of intake at chosen points on each curve, we can proceed to determine the quantitative effects of temperature on the rate of moisture intake. First we must know the ratio of the velocity at 20° to that of 5° C., and of the velocity at 35° to that at 20° C. These ratios for the intake velocities presented in tables XI and XII are given in table XIII.

In the earlier data, represented by table XI, if we take the average velocity at 5° C. as unity, we have the comparative mean velocities at 20 and 35° C. according to the ratio 1 : 2.05 : 2.05 × 1.83 = 3.75. Since the temperature of intake in the last curve

is 30° higher than the first, the mean value of Q_{10} will be obtained by extracting the cube root of the final term, 3.75, which is 1.55.

In the later data, table XII, the mean value of Q_{10} is higher. The final term of the ratio is 6.11, and its cube root 1.83. In both cases the value falls between the coefficient of temperature effects on physical and on chemical processes, but in the last case it approaches the van't Hoff coefficient. These figures are comparable with the value of Q_{10} obtained by BROWN and WORLEY for barley, as they have been obtained in exactly the same manner. The value of the temperature coefficient for *Hordeum* was 2.02.

BROWN and WORLEY considered that the velocity of intake was almost exactly an exponential function of the temperature. If it is,

TABLE XIII

RATIOS OF INTAKE VELOCITIES (*Xanthium*)

INTAKE PERCENTAGE	DATA TABLE XI		DATA TABLE XII	
	$\dfrac{\text{Velocity } 20°}{\text{Velocity } 5°}$	$\dfrac{\text{Velocity } 35°}{\text{Velocity } 20°}$	$\dfrac{\text{Velocity } 20°}{\text{Velocity } 5°}$	$\dfrac{\text{Velocity } 35°}{\text{Velocity } 20°}$
$y = 5.0$	1.88	1.72	2.39	1.81
$y = 7.5$	1.92	1.75	2.81	1.96
$y = 10.0$	1.97	1.80	3.17	2.12
$y = 15.0$	2.08	1.83	2.71	2.47
$y = 20.0$	2.18	1.90	2.92	2.35
$y = 25.0$	2.29	1.96	2.73	2.45
Mean ratios	2.05	1.83	2.79	2.19

logarithms of the velocities plotted against the temperature must lie in straight lines. They show in their second diagram such a plot of the logarithms, and state that the course of the lines in the diagram, in respect both of the straightness and of the agreement of inclination, furnishes evidence of a most conclusive character that the rate at which water is absorbed by barley seeds is an exponential function of the temperature. They call attention to the rarity with which physical properties show an exponential increase with rise in temperature, and then propose that the change is chemical and probably involves a simplification of the water molecule, as already stated.

The logarithms of the velocity of water intake by *Xanthium* seeds have been plotted similarly in fig. 3. The curves plotted

above the zero line represent the velocities for the earlier *Xanthium* data of table XI, while those below the zero line are from the later data from table XII. These curves will be discussed later.
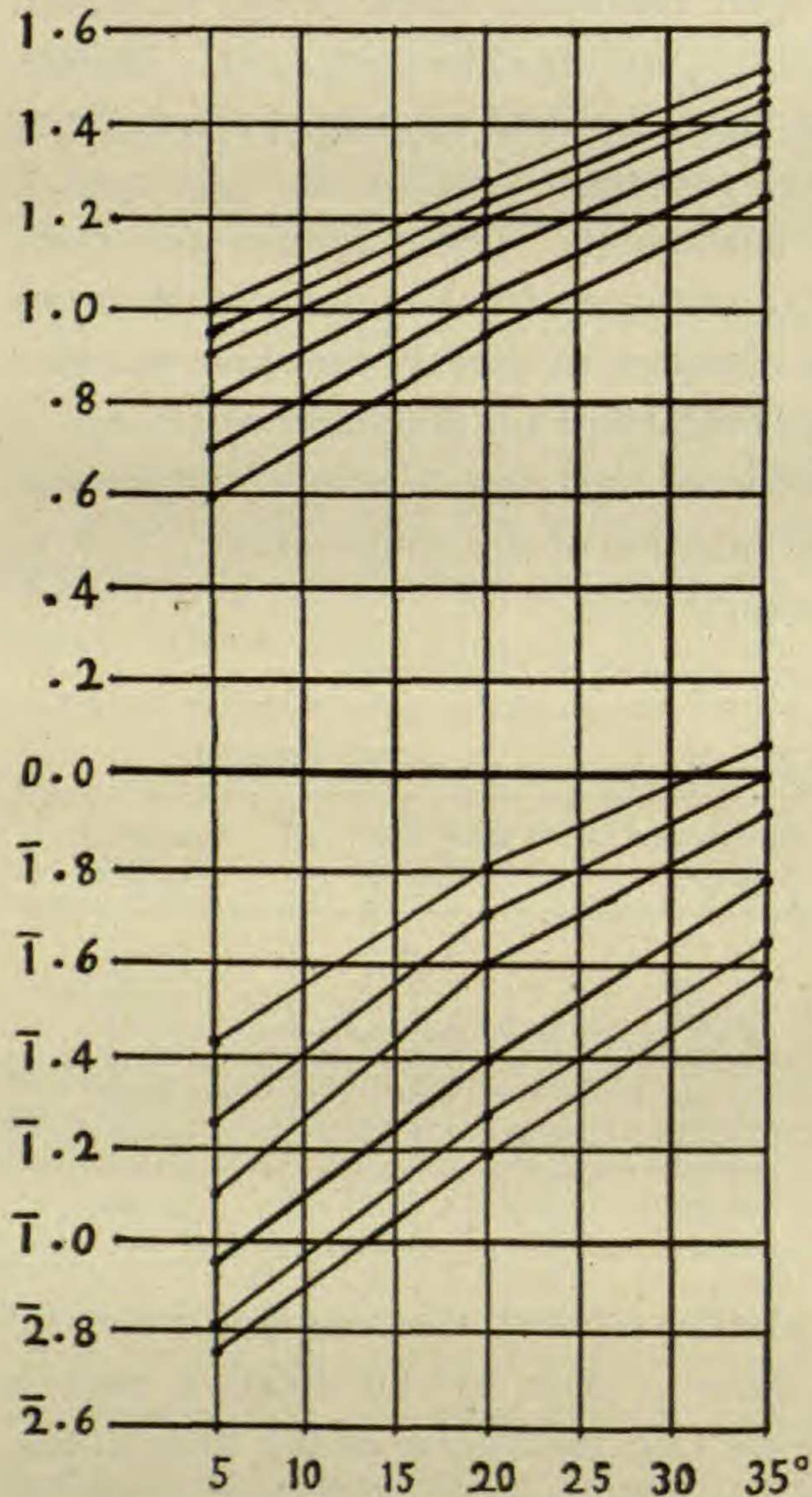

FIG. 3.—Logarithms of velocity plotted against temperature: upper series plotted from table XI, lower series from table XII; *Xanthium* seeds.

SPLIT PEAS

The split peas offered special difficulties from the mathematical side, and no attempt is made to present a complete account of the analysis of the data given in table VI. The variability of the data is much greater than in the case of cockleburs. The absorption is fairly consistent during the first hour, or, at high temperatures, during the first 15 or 20 minutes. After a certain critical percentage has been reached, however, they show a remarkable rise above the ideal curve indicated by the first part of the absorption. This critical percentage is about 20 per cent in the case of the Tom Thumb variety, about 23 per cent in the Canada Green field pea, and about 30 per cent for the Small Scotch Yellow commercial. The reasons for the rise in the rate of absorption will be considered in the general discussion.

As the Small Scotch Yellow gives us the longest period of consistent intake I shall present here data for this variety only,

and only for that portion of the curves which precedes the rise in rate.

Difficulties were encountered in choosing an empirical formula for the split pea data, owing partly no doubt to the fact that no duplicate tests were run, and the only set of data showed rather large irregularities at the beginning of the absorption. Curves closely approximating the data beyond 5 minutes ran below the point of origin. The one minute value ran quite too high in the 20 and 35° C. data, and somewhat too low in the 5° C. series. In any case the constant c in the formula was so small that it was thought best, after considering all possibilities, to run the com-

TABLE XIV

ALGEBRAIC CURVE FOR ABSORPTION DATA; SMALL SCOTCH YELLOW SPLIT PEA

Time (minutes)	5°			20°			35°		
	Low	Computed	High	Low	Computed	High	Low	Computed	High
1....	1.77	1.81	....	....	3.75	5.38	....	4.20	5.77
5....	....	7.25	7.26	13.26	13.27	....	16.34	16.41	......
10....	11.50	11.88	....	19.98	20.21	....	....	26.47	26.54
15....	....	15.30	15.58	....	24.93	25.09	33.65	33.73	......
20....	....	....	....	....	....	....	....	39.43	41.54
30....	....	22.16	22.48	33.69	33.84	....	....	....	......
45....	....	26.64	....	....	....	....	....	Break up	......
48....	....	....	....	....	40.30	43.01	....	....	......
60....	29.82	29.97	....	....	Break up	....	....	....	......
75....	....	32.62	36.37	....	....	....	....	....	......
		Break up							

puted curves through the point of origin, and omit that constant altogether. The generalized formula then takes the form $y = a \log_{10} (bx+1)$.

The three formulae, for the 5, 20, and 35° C. curves for the Small Scotch Yellow peas, with values of a and b substituted, are as follows:

$$5° \text{ C.}: y = 30.13 \log_{10} (0.148x+1)$$
$$20° \text{ C.}: y = 34.58 \log_{10} (0.284x+1)$$
$$35° \text{ C.}: y = 60.90 \log_{10} (0.172x+1)$$

Using these empirical formulae, we have secured a fair agreement between calculated and observed intake, not so close as in the case of *Xanthium*, but much closer than is frequently obtained

in attempts to reduce biological phenomena to mathematical expressions (see table XIV).

The velocity of intake at the same six percentages used for the *Xanthium* seeds has been calculated from the tangents to the curves. The velocity in percentage per minute, and the logarithms of the velocities are shown in table XV.

TABLE XV

WATER INTAKE IN SMALL SCOTCH YELLOW SPLIT PEA

INTAKE PERCENTAGE	5°		20°		35°	
	Velocity in percentage per minute	Log_{10} velocity	Velocity in percentage per minute	Log_{10} velocity	Velocity in percentage per minute	Log_{10} velocity
$y=5$........	1.32160	0.121100	3.05728	0.485335	3.76544	0.575827
$y=7.5$.....	1.09175	0.038122	2.58846	0.413041	3.42593	0.534779
$y=10$........	0.90188	$\bar{1}$.955148	2.19152	0.340745	3.11692	0.493725
$y=15$........	0.61546	$\bar{1}$.789200	1.57091	0.196151	2.58002	0.411623
$y=20$........	0.42000	$\bar{1}$.623249	1.12605	0.051558	2.13562	0.329524
$y=25$........	0.28662	$\bar{1}$.457306	0.80717	$\bar{1}$.906965	1.76775	0.247421

The ratios of the intake velocities for the split peas were obtained from the data of table XV, and are presented in table XVI.

TABLE XVI

RATIOS OF INTAKE VELOCITIES; SMALL SCOTCH YELLOW SPLIT PEAS

Intake percentage	$\dfrac{\text{Velocity } 20°}{\text{Velocity } 5°}$	$\dfrac{\text{Velocity } 35°}{\text{Velocity } 20°}$
$y=5$................	2.31	1.23
$y=7.5$.............	2.37	1.32
$y=10$..............	2.43	1.42
$y=15$..............	2.55	1.64
$y=20$..............	2.68	1.90
$y=25$..............	2.82	2.19
Mean ratio......	2.53	1.62

From the mean ratios we find that the value of Q_{10} in this case is 1.6, or just a little higher than the earlier determination for *Xanthium*. Since the calculations in the case of split peas are made from single equation curves, all passing through the point of

origin, they offer the best possible opportunity to study the question of straight line plots of logarithms against temperature.   These are shown in fig. 4. It is seen that they are decidedly not straight lines.

Having now presented in some detail the results of the mathematical analysis of the data, which has been carried out in such a way as to make possible a comparison between this work and that of BROWN and WORLEY, I shall discuss briefly the significance of the results.
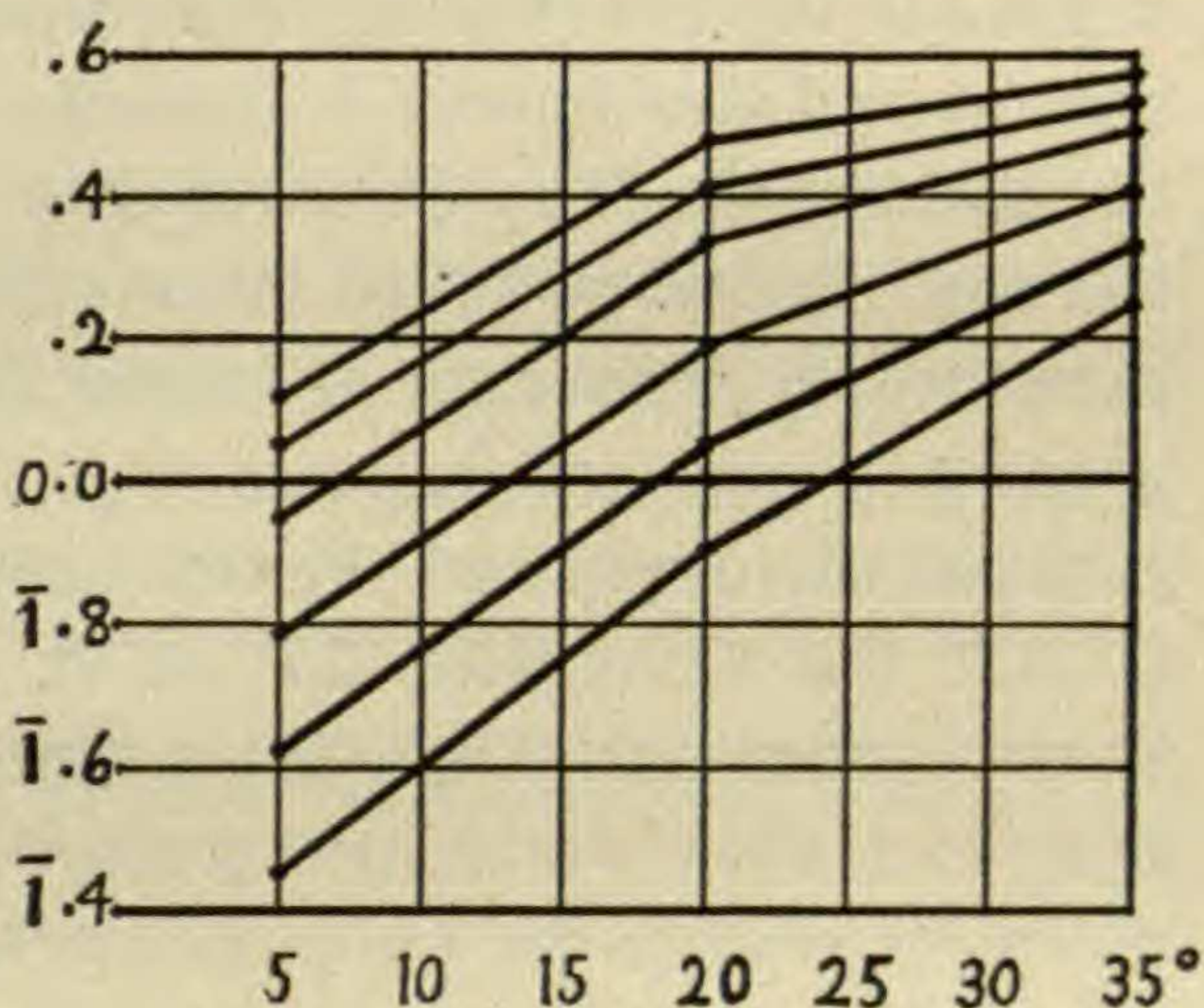

FIG. 4.—Logarithms of velocity plotted against temperature, split peas, table XV.

Discussion

There are several features of the work by BROWN and WORLEY which need to be considered in judging its value. Attention was called in the introduction to the rather rough method of securing tangents, which, however, was quite skilfully used. In view of the fact that the early phases of absorption were not studied by them, however, it is possible that the tangents they obtained between the point of origin and the first intake data at each temperature would not agree with those of a curve plotted at close intervals. If the barley seeds were to show a large initial intake, the curve would be thrown upward from the base, and the succeeding portion of the curve would have a different course, affecting the very portion of the curve where the tangents are measured in determining intake velocities. It is this early part of the curve which is important, for the tangents are measured for that part of the curve between the origin and 25 per cent of intake.

The greatest disadvantage in the data supplied by BROWN and WORLEY is the long time interval between observations, and especially the long first interval. Their first observations were taken at 5–6 hours after the beginning of absorption. If I had waited 5 hours for the first observations in any of the work presented

in this paper, all of the tangents used in measuring intake velocities would have fallen on that part of the curve between the point of origin and the first reading, all of which is constructed from imagination, as an "ideal curve." In the case of barley it is not so serious, but it is only in the 3.8° curve that all of the tangents fall beyond the first observation. In their 21.1° curve the first observation showed over 9 per cent of intake, from which it is seen that the 5 and 7.5 per cent tangents were measured on a "guess curve" between the origin and the first observation, and the 34.6° curve is still less favorable; for in it the first observation shows nearly 17 per cent of intake, so that 4 out of 6 tangents used were measured on a curve constructed entirely without data. This matter is vital to the whole theory they propose, for they had but three points in plotting logarithms of velocities against temperatures, and if one of the points is insecure no conclusions can be drawn. The other two points are bound to be in a straight line. In four cases out of six, the third point is not established by data, and in two of the plotted logarithm-temperature curves, both the second and the third points are derived from tangents whose determination is insecure. The evidence offered, therefore, that the velocity of intake is an exponential function of the temperature, is not very convincing. In this work I have used short time intervals to understand better the curve whose tangents were to be measured. Our short intervals have the disadvantage that water movement goes on in the seed during weighing which occurs frequently. There is no intake during weighing, of course, but distribution of water already taken in continues. I have felt that the advantages of the close intervals between weighings exceed by far any disadvantage that might exist.

In the case of *Xanthium*, with a semipermeable coat, and in split peas without the coat, I have found that the plotting of logarithms of velocity against temperatures does not yield straight lines. The nearest approach to straight lines is seen in the upper half of fig. 3, but even here there is a slight divergence, always in the same direction. A somewhat greater divergence from straight lines is seen in the lower half of fig. 3, and a very marked divergence is seen in fig. 4, in the case of split peas. From the data I conclude

that plotting logs of velocities against temperatures will yield some kind of a curve, but there are not enough data at hand to determine anything as to the character of the curve. The general conclusion to be drawn from this part of the work is that the evidence, as far as it goes, is rather against the assumption that the velocity of intake is an exponential function of the temperature.

Another point that deserves notice is the nature of the curves of water intake. BROWN and WORLEY called their curves paraboloid and described them as running out toward a common asymptote. The language, of course, must have been intended in a very loose sense, for parabolic curves passing through a common point of origin, as theirs do, could never have a common asymptote. It was found impossible to fit a parabolic formula to the intake data presented, but from the figures given in tabular form (tables VII–X and XIV) it is evident that the logarithmic curve $y = a \log_{10} (bx+1) + c$ may be made to fit the data very closely. Furthermore I have taken the $3.8°$ barley data and attempted to fit to it both the logarithmic and a hyperbolic equation made to pass through the origin and the second and fourth values of their data. I have found that the logarithmic equation fits much closer to their data than the hyperbolic equation. The two sets of values and the original data are given for comparison. The time and data columns are from BROWN and WORLEY.

Time	Data	Computed (logarithmic)	Computed (hyperbolic)
5.58 hours	4.42	4.41	5.21
24.75 hours	11.82	11.82	11.82
48.83 hours	18.52	18.49	17.99
72.25 hours	23.42	23.43	23.42
96.50 hours	27.42	27.56	28.78
144.25 hours	34.02	33.89	38.99

The logarithmic equation used in this comparison is $y = 48.6 \log_{10} (0.025x+1)$, and the hyperbolic equation, $y = 0.2024 \sqrt{x^2 + 112.988x}$.

Considering the closeness of agreement which is obtainable with the logarithmic formula, it seems more reasonable to consider the curves of water intake, even in the case of barley seeds, as logarithmic rather than hyperbolic.

If the velocity of absorption were an exponential function of the temperature, the relation between temperature and the rate of entry of water into the seeds might be expressed by an equation of the form $v = ae^{k\theta}$ in which θ is the temperature. As I have obtained evidence somewhat adverse to the assumption that velocity of absorption is an exponential function of the temperature, this equation does not hold. Wherever the logarithmic formula $y = a \log_{10}(bx + 1) + c$ holds for the curves of absorption, the velocity of intake may be represented by the formula $v = ae^{-k\phi}$ in which ϕ is the percentage of water already absorbed. In other words, the velocity of intake is approximately an inverse exponential function of the total preceding absorption. It is not claimed that this is true for all cases of absorption, but that it is just as true as the logarithmic equation used. Wherever that equation holds, the velocity formula holds.

The chief interest centers in the temperature coefficient of absorption. I have obtained coefficients ranging from 1.55 to 1.83 in *Xanthium* seeds, and 1.6 in split peas. These are all above the temperature coefficient of physical changes, and below that for chemical change. BROWN and WORLEY obtained a value above 2, and adopted the idea that absorption was conditioned as to rate, in the case they studied, by some chemical change. In seeking a chemical change to account for their observations, they suggested that the semipermeable seed coat of barley was involved in a special way, in its relation to complex or simplified water molecules. They suggested the possibility that the differential septum (semipermeable coat) permits only hydrone to penetrate it, and that the temperature rise increases the proportion of hydrone in solution. One of the main difficulties in the way of accepting such a hypothesis as to the relation of hydrone to semipermeable membranes, is its implication that all semipermeable membranes should behave alike. *Xanthium* and *Hordeum* both have semipermeable membranes, and if the rate of water passage depended solely on the proportion of hydrone, treatment of either seed should give the same results. It is a notable fact, however, that semipermeable membranes are always individualistic. Each kind has its own behavior, no two

kinds acting exactly alike. It would not be possible to accept without modification any theory which assumes that differential septa are alike in behavior. I do not mean to say that water is not simplified in structure as it is warmed, nor that such a change would not increase the rate of absorption, but it seems entirely possible to account for the high temperature coefficients found in absorption phenomena without the necessity of assuming such a change, or making it the sole change involved in the process. The substances of which the seeds are composed, membranes, embryo, and storage products, are all largely colloidal. These colloidal materials undoubtedly are modified in state of aggregation by being subjected during wetting to low or high temperatures. Higher temperatures usually increase dispersion and increase the water-holding capacity of organic colloids, and lower temperatures reverse the process. It does not seem possible that such changes could be absent during absorption, and they must go far to explain the differences in intake rates and the values of Q_{10}, which stand between those found for purely physical and purely chemical processes. Absorption is a complex process, probably involving both physical and chemical factors, and the values of Q_{10} may be considered the resultant of the effects of temperature on both classes of factors. The fact that we get about the same value for Q_{10} in absorption without a semipermeable coat as with such a coat indicates that the membrane is not necessarily the rate determining factor.

DENNY (2) has shown that membranes differ greatly in their power to transmit water. If the seed coat transmits water more slowly than seed substance can absorb it, the transmission rate is a limiting factor on the absorption rate. If the transmission power of the coat exceeds the absorption power of the seed substance, however, the latter determines the rate. Again, if seed coat, embryo, and endosperm form a very non-homogeneous structure, the absorption rate may be dominated first by one of the structures, and later by the others in succession, giving peculiar absorption curves, difficult to analyze mathematically.

It was noted that *Xanthium* seeds showed a very rapid initial intake during a minute or less, after which the rate broke sharply to a

lower rate. Two explanations suggest themselves for this. The coat may absorb water more readily than seed substance, and the initial intake may represent the saturation of the seed coat, or the rapid initial intake may be caused by the fact that at first the absorbing substance and water are in direct contact, but after a short time the water absorbed by the interior of the seed must penetrate a layer of saturated substance before it can reach the actively absorbing material. This outer saturated layer may offer resistance to intake in the form of friction with the moving water. As this layer becomes thicker and thicker all the time, it may tend more and more to reduce the absorption rate. Changes in the velocity of absorption due to such causes might be found in any case of water intake.

Finally, something should be said about the rise in the intake rate in split peas after a certain critical percentage of intake has been reached. During absorption one can observe that the hemispherical cotyledons become swollen first around the thin edge where water is penetrating from both sides. Looking at the flat side of the cotyledon, one can see that the edge has become raised up, while the center remains as it was originally, and appears depressed. The flat side has become concave. It seems evident that a band of dry material extends across the middle of the cotyledon from the center of the spherical side to the center of the flat side, and that imbibition forces at work in the edge of the seed are pulling at this dry band. After the critical intake has been reached, the center of the flat side soon swells out, and the concavity disappears. It is practically certain that the seed substance actually cracks apart during this process, leaving interior cavities that fill up with water. This idea is strongly supported by unpublished data, collected by DUDLEY J. PRATT, who worked in the laboratory of the University of Kansas, on the effects of acids and bases on the swelling of pea cotyledons. He was able to detect clearly the formation of such cavities during absorption, and some of them are of considerable size, as when strong hydrates or acids cause excessive swelling. This breaking up of the internal tissues of the cotyledon satisfactorily accounts for the peculiarities observed in absorption curves in split peas.

It is my conviction, after a number of years of experience with absorption phenomena, that absorption is a complex process dependent on a number of factors, some of which may be external, but many of which are internal. I have become convinced that we should not expect a single formula or rate law to apply to absorption in general. Each case of absorption is likely to present a problem in itself, and to differ, slightly at least, from any other case, because of both qualitative and quantitative differences in the numerous factors determining absorption rates.

Summary

1. This paper deals with the quantitative influence of temperature on the velocity of moisture intake by certain seeds, chosen for the presence and absence of semipermeable coats. *Xanthium pennsylvanicum* Wallr. and commercial and garden peas were used, the latter with coats removed.

2. The curves of water intake were found to be complex, but can be represented by a logarithmic equation or series of equations of the form $y = a \log_{10}(bx + 1) + c$.

3. The analysis of the data presented does not support the theory of BROWN and WORLEY that the velocity of intake is an exponential function of the temperature, but the velocity of intake at any given moment in the seeds studied is approximately an inverse exponential function of the amount of water previously absorbed.

4. The mean value of Q_{10} in *Xanthium* seeds was in one instance 1.55, in another 1.83, and in split peas of the Small Scotch Yellow variety 1.6.

5. These values do not indicate that absorption is conditioned by some single chemical change like simplification of water to hydrone as the temperature rises, but are believed to indicate that absorption at different temperatures involves both physical and chemical changes.

6. The main chemical changes with rise of temperature are believed to occur in the colloids of the seed, and semipermeability, as such, is thought not to be an important factor in determining the rate of water absorption.

7. The paper considers critically the methods and interpretation of the similar work of BROWN and WORLEY on *Hordeum* seeds.

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